

Phase asymmetry effect in longitudinal offset coupled resonator optical waveguides

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Abstract

We show that the implementation of the longitudinal displacement technique for adjusting the coupling coefficients in microring waveguides is subject to a phase asymmetry effect. This issue is shown to substantially alter the system response in apodized filters and cannot be ignored in the design stage.

1 Introduction

Coupled microring structures are small-size, compact optical devices which provide photonic processing functionalities such as optical filtering [1, 2], dispersion compensation [3], optical sensing [4], or the control of the group delay (slow and fast light) [5], [6]. Group delay control is particularly important for the development of high-performance photonic networks, where ways to obtain large, distortionless propagation delays are currently sought after. The research in slow light has made intensive use, at least as a starting point, of the two “basic” MRR structures : the Side Coupled Integrated Spaced Sequence of Resonators (SCISSOR) [7], and the Coupled Resonator Optical Waveguides (CROW) [8]. Unlike the SCISSOR, which is an all-pass structure, that is, a pure phase filter, the CROW has four ports and is functionally equivalent to a Bragg grating. Motivated by this analogy, the technique of apodization or windowing, borrowed from the field of digital filter design and regularly employed in grating filters [9], has also been proposed to improve the characteristics of CROW structures [10]. Basically, apodizing the coupling constants of the coupled waveguides in the unit cells helps to reduce the side-lobes in the SCISSOR and the ripples in the pass-band of the CROW.

A general difficulty of the MRR designs is to attain the high accuracy required in the values of the coupling constants (K) when it comes to the fabrication process. Typically, the adjustment of the K values is accomplished by changing the separation between the waveguides of the coupler (transversal offset). This is a demanding technique which restricts the possibilities of design

because it may require, along the longitudinal direction, resolution steps below the current fabrication limit (of the order of a few nm). To overcome this difficulty, a much less stringent technique was proposed in [11]. Here the coupling constant values are adjusted by longitudinal offset between the coupled waveguides, while the inter-guide separation is left fixed. The resolution requirements are relaxed by two orders of magnitude, making photolithographic production feasible. This technique has been demonstrated in [12] for a 3-racetrack apodized CROW structure fabricated in silicon-on-insulator.

Despite the general good agreement between the expected and the measured results in the structure considered in [12], we identify in this letter a fundamental problem which is inherent to all apodized CROW structures designed by the longitudinal offset technique. We will review the derivation of the CROW transfer function, paying particular attention to the role of the directional couplers implemented using the longitudinal displacement method. With the obtained results, we demonstrate the actual performance degradation occurring in these devices.

2 Model

The geometry of a three ring CROW with longitudinal displacement couplings is shown in Fig. 1, including the definition of the field variables E_l^+ and E_{l-1}^- . E_{N+1}^- will be assumed to be null and its phase reference is left undefined. L_c is the length of the straight waveguide sections and corresponds to the coupler length for zero lateral displacement, $L_R = \pi R$, is the length of each curved waveguide section of radius R . The total ring length is, therefore, $L_T = 2L_R + 2L_c$ and will be assumed constant in this work. For simplicity, we will ignore the actual correction in the coupling length due to the curved sections [13] and set $L_{eff} = L_c$.

It is well known that the accumulated propagation phase for any of the output field components of the lossless coupler of length L is $\exp(j\beta L)$ [14], where β is the propagation constant of the mode of each of the individual waveguide sections that are combined in the coupler. Therefore, if we call $E_{o,1}$ $E_{o,2}$ the complex field amplitudes at the output ports of a coupler, and $E_{i,1}$ $E_{i,2}$ those at the input, we have

$$\begin{bmatrix} E_{o,1} \\ E_{o,2} \end{bmatrix} = \begin{bmatrix} t & \kappa \\ -\kappa^* & t \end{bmatrix} \begin{bmatrix} E_{i,1} \\ E_{i,2} \end{bmatrix} \exp(j\beta L) \quad (1)$$

with κ and t the parameters defining the coupler behavior.

The common phase factor $\exp(j\beta L)$ permits to model the coupler as a lumped element localized at the input plane and described by Eq. (1) excluding the phase term that is included in the propagation model. The positions of the coupling points are marked with horizontal dashed lines in Figure 1 and correspond to the reference planes for the field variables.

The equation relating the fields in the rings l and $l+1$ can be readily written

with a general notation as

$$\begin{bmatrix} E_{l+1}^+ \\ E_{l+1}^- \end{bmatrix} = \mathbf{M}_l \begin{bmatrix} E_l^+ \\ E_l^- \end{bmatrix} \quad (2)$$

with

$$\mathbf{M}_l = \frac{1}{\kappa_l} \begin{bmatrix} -(|\kappa_l|^2 + |t_l|^2) \exp(j\delta_l^+) & t_l^* \\ -t_l \exp[j(\delta_l^+ - \delta_{l+1}^-)] & \exp(-j\delta_{l+1}^-) \end{bmatrix} \quad (3)$$

and $\delta_l^+ = \beta L_l^+$, $\delta_l^- = \beta L_l^-$, where we have assigned a total propagation length L_l^+ to the forward propagating signal in ring l , and a length $L_l^- = L_T - L_l^+$ to the backward component, as illustrated in Figure 1. For simplicity, we have assumed negligible propagation losses. The expressions of L_l^+ and L_l^- are given below for some specific cases.

For an ideal evanescent coupler of the type described in Figure 1, we have $\kappa_l = j\sqrt{K_l}$ and $t_l = \sqrt{1 - K_l}$, where K_l is the coupling constant for the l -th coupler. The overall output-input relation can then be written as

$$\begin{bmatrix} E_{N+1}^+ \\ E_{N+1}^- \end{bmatrix} = \mathbf{M} \begin{bmatrix} E_0^+ \\ E_0^- \end{bmatrix} \quad (4)$$

with

$$\mathbf{M} = (-j)^N \prod_{l=0}^N \frac{1}{\sqrt{K_l}} \times \begin{bmatrix} -\exp(j\delta_l^+) & \sqrt{1 - K_l} \\ -\sqrt{1 - K_l} \exp[j(\delta_l^+ - \delta_{l+1}^-)] & \exp(-j\delta_{l+1}^-) \end{bmatrix}. \quad (5)$$

The exact expressions of the propagation phase shifts will vary for each particular geometry implemented. For an all-downwards arrangement as the one depicted in Figure 1 (a) we have, for $l \neq 0$ and $l \neq N$,

$$L_l^+ = \begin{cases} L_C + L_R + L_{\text{off}}^l - L_{\text{off}}^{l-1} & \text{if } l \text{ even} \\ L_C + L_R & \text{if } l \text{ odd,} \end{cases} \quad (6)$$

and $L_l^- = L_T - L_l^+$.

For an alternating arrangement, such as the one shown in Figure 1.b, we have for $l = 1, \dots, N-1$,

$$L_l^+ = L_c + L_R + L_{\text{off}}^{l-1} + L_{\text{off}}^l, \quad (7)$$

and $L_l^- = L_T - L_l^+$.

In either case we have $\delta_0^+ = \beta (L_R/2 + L_{\text{off}}^0)$ if $l = 0$ and, if $l = N$, $\delta_{N+1}^- = 0$.

3 Results and discussion

In general, the phase asymmetry will greatly affect the system response in such a way that any resemblance with the original target transfer function can be completely lost, but the effect is largely dependent of the filter geometry and can be controlled if it is considered in the design stage of the optical filter.

If the all-downwards configuration of Figure 1 (a) is chosen in the implementation of a CROW with constant coupling coefficients using the longitudinal displacement technique, there is no phase asymmetry since L_{off}^l is constant and the terms producing the asymmetry in (6) cancel out. Similarly, it can be shown that the amplitude response obtained in the non-apodized case with the alternating configuration of Figure 1 (b) corresponds to that of the ideal case.

However, in apodized filters the phase asymmetry produced by the variation of the offset lengths along the CROW waveguide introduced to modulate the coupling coefficients results in a severe distortion of the system transfer function as compared to the targeted design.

We apply our findings to the experimental results reported in [12]. We use the same parameters as in the $N = 3$ fabricated filter with $n_g = 2.24$, $R = 5 \mu\text{m}$, $L_s = 53.3 \mu\text{m}$ coupling constants $\{K_l\}_{l=0}^3 = \{0.86, 0.54, 0.54, 0.86\}$ and $\{L_{off}^l\} = \{10.56 \mu\text{m}, 2.42 \mu\text{m}, 2.42 \mu\text{m}, 10.56 \mu\text{m}\}$. The geometry is that of Figure 1 (c). In this case we have $L_1^- = L_c + L_R$, $L_2^- = L_c + L_R + L_{off}^1$, $L_3^- = L_c + L_R + L_{off}^2 - L_{off}^3$ and $L_l^+ = L_T - l_l^+$. The amplitude response of the ideal apodized filter is shown with dashed lines in Figure 2, whereas the calculated amplitude response including the phase asymmetry is shown in the same figure with solid lines.

In spite of our simplifying assumptions, the correspondence of the calculated curve with the experimental measurements in the spectral region between 1550 nm and 1554 nm displayed in the Figure 4 of Reference [12] is remarkable.

The effect of the phase asymmetry is shown to destroy the periodicity of the system response. Even though a very good fit with the ideal response is found for a limited spectral range, the resemblance with the target system response can be completely lost in other spectral regions. We note that in this case it is by chance that good correspondence has been obtained in the region of interest, since no a priori provision for the effect of phase asymmetry was made in the design.

In conclusion, we have highlighted the existence of a phase asymmetry effect in the implementation of CROW filters using the lateral displacement technique. We have shown that even though certain filter geometries of non-apodized filters can be safely implemented, this effect cannot be ignored in the design of apodized CROWS.

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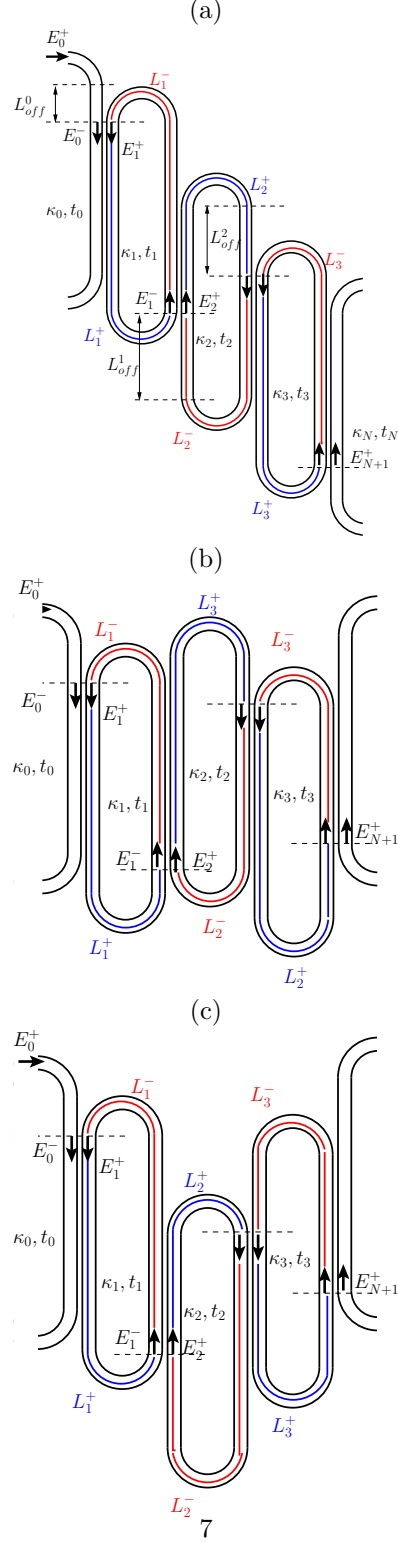


Figure 1: Layout of a $N = 3$ ring CROW with longitudinal offset coupling. (a) with all the lateral displacements produced downwards, (b) with alternating directions for the lateral displacements and (c) three rings with the two first couplings arranged downwards and the two last ones upwards, as in Ref [11].

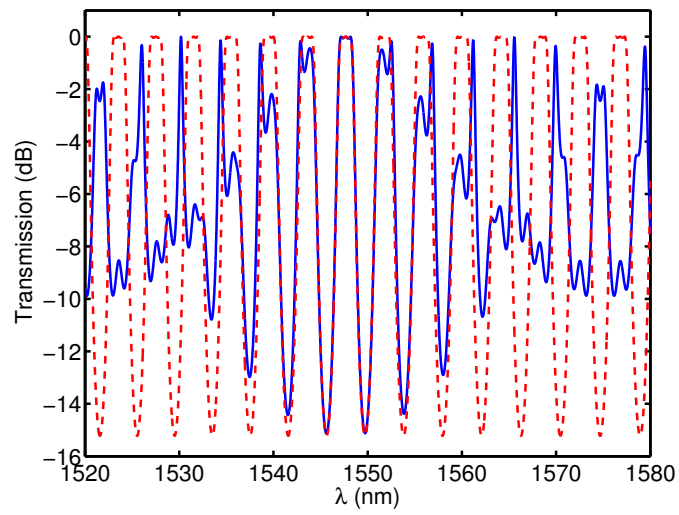


Figure 2: Transmission spectra for the three-ring CROW design with (solid line) and without (dashed line) the effect of phase asymmetry.